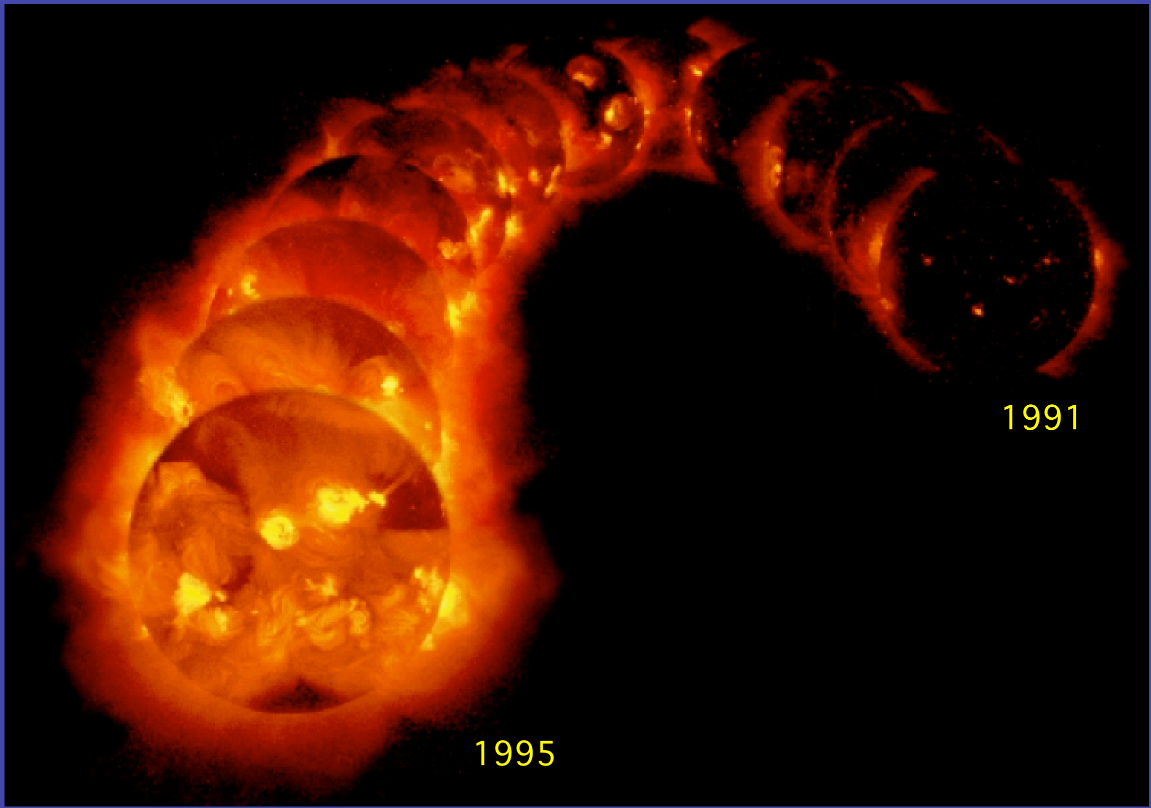
In the News…



X-ray emission from the solar corona as seen by the Yohkoh (“sunbeam”) solar observatory

The Solar Activity Cycle

The Sun varies from an “inactive” to “active” state. When “active” there’s lots of solar flares, many sunspots, and a larger, hotter corona. The activity cycle is composed of 2 sub-cycles lasting 11 years each, for a total cycle length of 22 years

Stars

- Definition
- General properties of Stars: temperatures, radii, luminosities, compositions, masses
- Energy Generation
- Stellar interiors
- Stellar Atmospheres
- The Sun

What is a star?

A star is a gravitationally bound accumulation of matter. It has these properties:

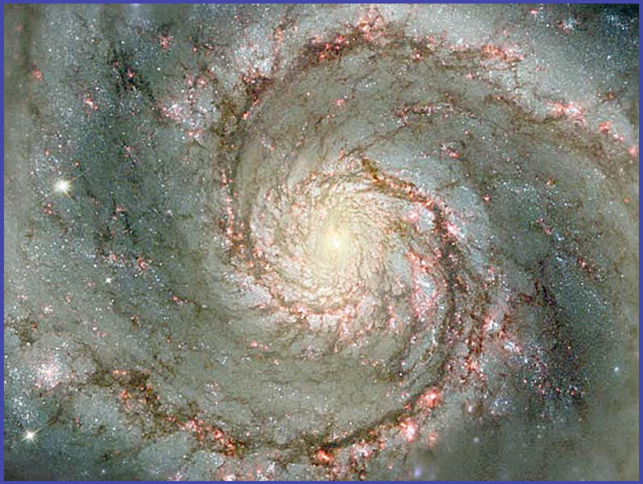
- hydrostatic equilibrium - weight of outer layers supported by gas pressure from inner layers
- energy generation - stars produce energy in their interiors
- energy equilibrium - internal energy generated in the interior exactly equaled by amount of energy released from surface

These properties are defined by the equations of stellar structure, which are used to calculate stellar models.

Spatial Distributions

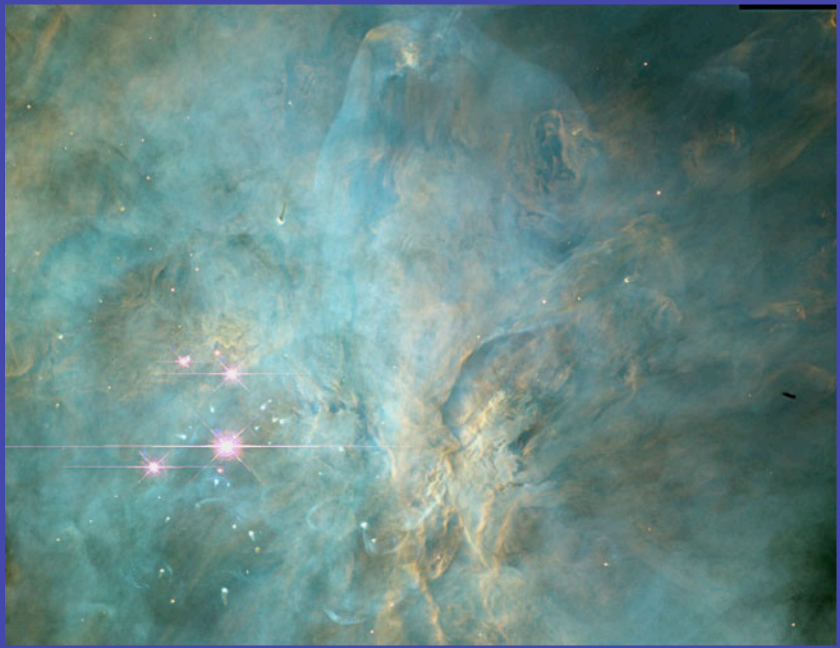
Stars are not uniformly distributed in space

Stars exist in galaxies



Stars are not uniformly distributed in galaxies

Neighborhoods



center of the Orion Nebula

Stars form where gas and dust are most dense

typically stars form in groups called clusters

Stars move - older stars may move away from their birthsites; stars can explode out of a galaxy

Observational Properties

Stars characterized by:

1. Brightness
2. Surface Temperature
3. Distance
4. Size
5. Luminosity
6. Mass
7. Composition

Of these the easiest to measure are 1 & 2

The Solar Spectrum

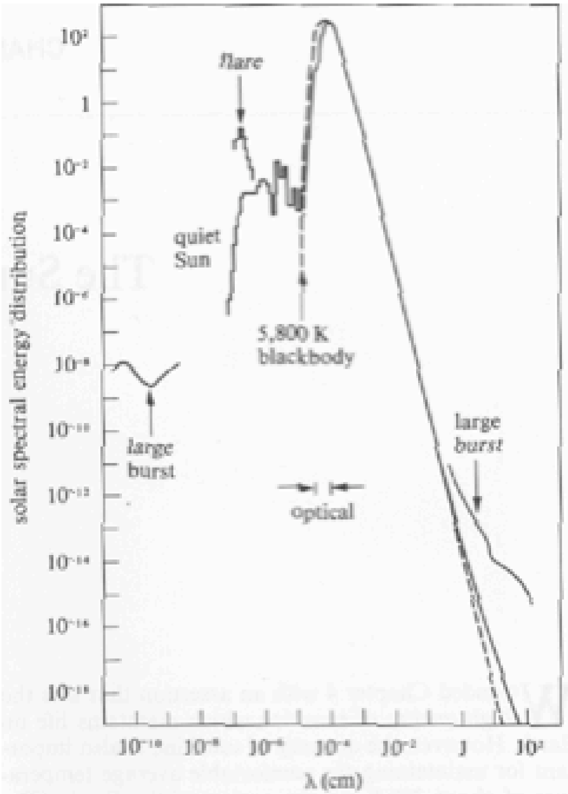


Figure 5.1. The solar spectral energy distribution.

Example: the sun

Solar Spectrum with absorption lines

Notice that the dark lines in the solar spectrum correspond to the emission lines of the various elements. This is because atoms can absorb or emitt at the same wavelengths.

Visible solar flux emphasizing the continuum and absorption line spectrum

Hotter stars look bluer, cooler stars redder

The Absorption Spectrum

Stellar spectra have dark bands called absorption lines produced by photo-excitation in the cooler layers of the stellar atmosphere just above the stellar surface.

The types of absorption lines depend on

- temperature (via the spectral distribution of photons)
- composition

Common Spectral Lines

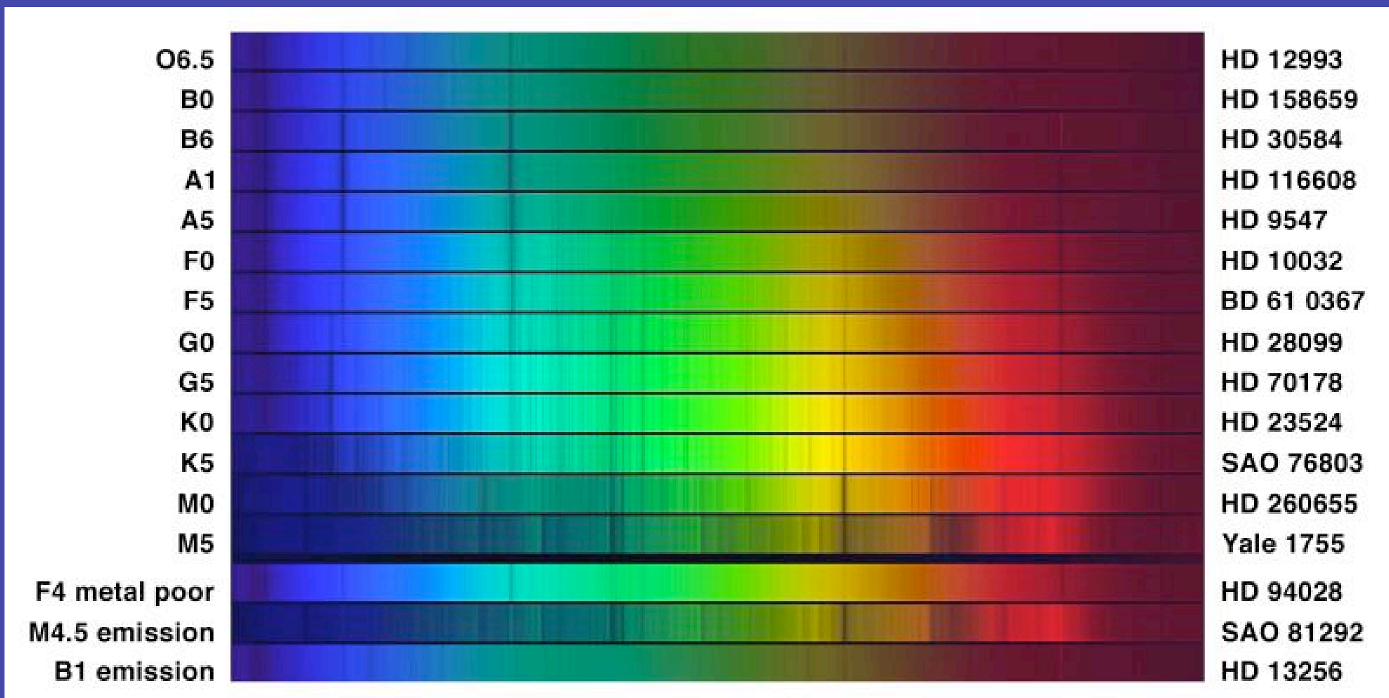
Common Spectral Lines (given in angstroms)

Hydrogen "Balmer series"		Metals	
H a	6563	C II	4267
H b	4861	C III	4649, 5696
H g	4340	C IV	4658, 5805
H d	4101	N III	4097, 4634
H e	3970	N IV	4058, 7100
Helium		N V	4605
He I	4026, 4388 4471, 7065	O V	5592
		Na I	5890
He II	4339, 4542, 4686	Mg II	4481
Molecular Bands		Si III	4552
CH "G band"	4300	Si IV	4089
CN	4215	Ca I	4226
C_2	4697	Ca II	3933, 3968
TiO	4584, 4625 4670, 4760	Sc II	4246
		Ti II	4300, 4444
MgH	4780	Mn I	4032
Telluric absorption bands		Fe I	4045, 4325
5860-5990	6270-6370	Fe II	4175, 4233
6850-7400	7570-7700	Sr II	4077, 4215

http://www.noao.edu/outreach/tlrbse/iphelps/stellar3.html

Stellar Spectral Types

Spectral sequencing was first done in the late 19th century based on stellar color and the strength of the absorption lines of hydrogen.



Sp. Type	Temperature
O	> 30000K
B	12000-30000K
A	8000-12000K
F	6000-8000K
G	5000-6000K
K	4000-5000K
M	2000-4000

Eventually the relation between stellar temperature and spectral type was recognized and the sequence organized: OBAFGKM

Stellar compositions

Most stars are mainly composed of hydrogen (75% by mass) and He (24% by mass)

Composition can be determined from measured relative depths of stellar absorption lines, if the underlying stellar continuum is known

Broad-Band Photometry

Stellar temperatures/spectral types can be characterized by comparing the brightness of the star as seen through two or more filters.

3 standard filters: U, B, V

Stellar color defined as the brightness difference in magnitudes seen (usually) in B & V filters: color=B-V

magnitude is related to flux as

$$B-V=-2.5 \log (f_B/f_V)$$

where f_B and f_V are the fluxes seen through the B and V filters

Recall: numerically higher magnitude= fainter

Apparent and Absolute Brightness

Astronomers define Absolute Magnitude to provide a measure of intrinsic stellar brightness

$$m - M = 5 \log (D/10)$$

where M is the absolute magnitude, m the apparent magnitude and D the distance to the star in pc.

m-M is called the distance modulus

Luminosity Class	**Description**
Iab	Supergiant
II	Bright Giant
III	Giants
IV	Subgiants
V	Dwarf (Main Sequence)

Extinction and Reddening

Intervening gas and dust in front of a star causes:

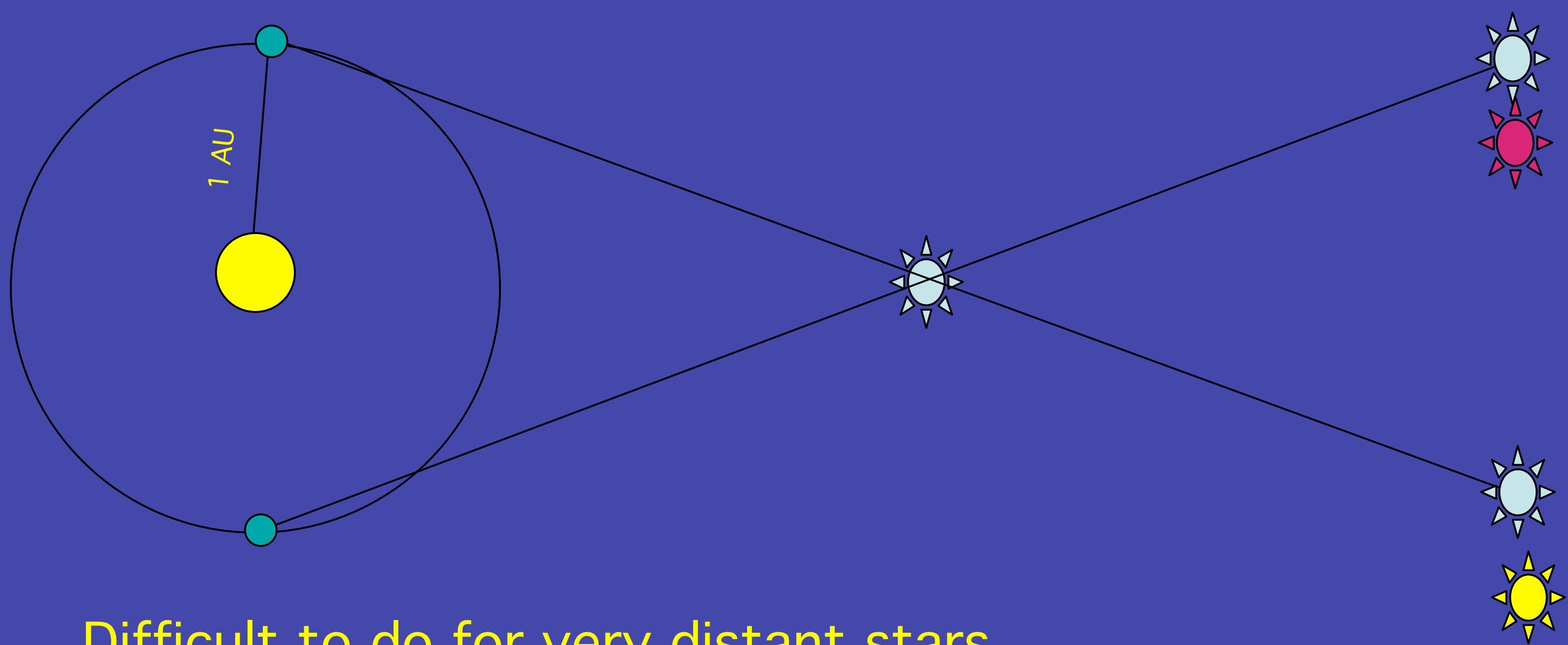
- extinction: star looks fainter
- reddening: star looks redder

If the temperature of the star can be determined (by assessment of the absorption lines, for eg.) then the observed spectrum can be compared to the real spectrum for that temperature and the reddening determined.

After the reddening is determined, the amount of extinction can be determined, and de-reddened & un-extincted brightness can be derived.

Stellar Distances

Star distances can be determined in a number of ways.
Most accurate is via stellar parallax



Difficult to do for very distant stars...

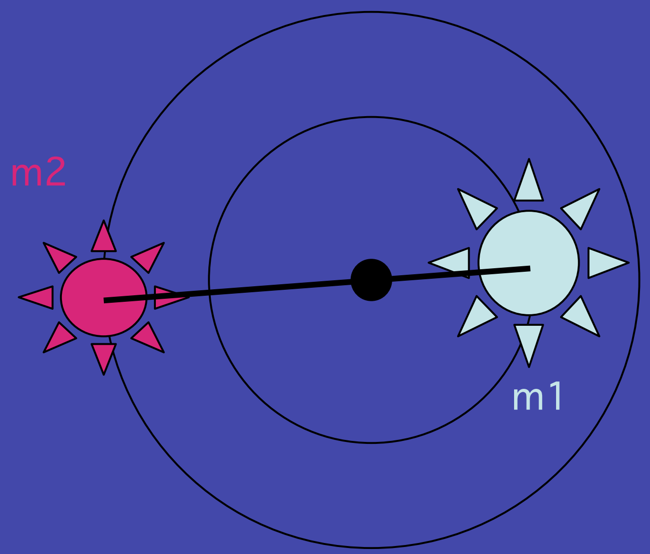
Stellar Masses

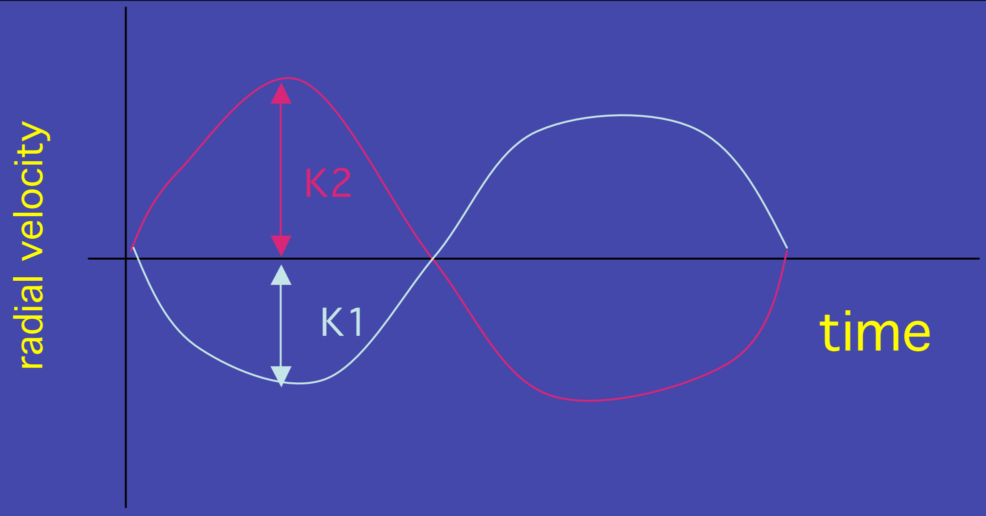
Most accurate measures of stellar masses come from observations of binary stars

If absorption lines from both stars seen (double-lined spectroscopic binary) then the radial velocities of both stars (i.e. velocity along the line of sight) around the orbit can be measured. The relative amplitudes of the radial velocity curves for the 2 stars give the mass ratio.

The total mass can be derived from the measured period using Kepler's 3 law.

Example: Circular orbit

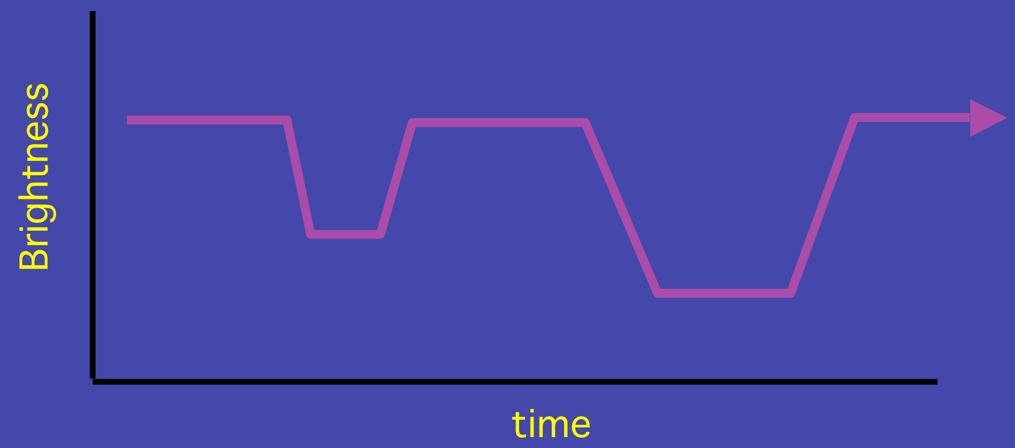


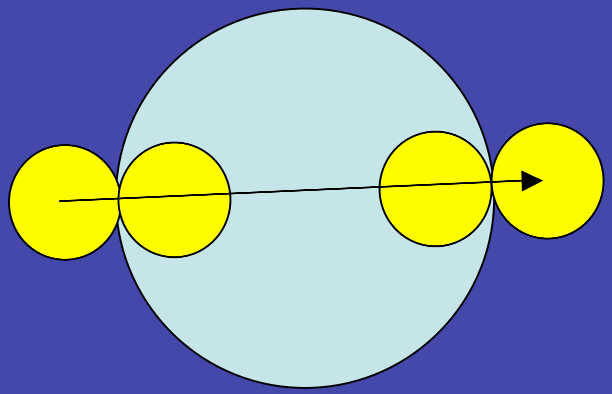


$$r = [(K_1 + K_2)/\Omega]/\sin(i)$$
$$m_2/m_1 = K_1/K_2$$
$$(m_1 + m_2) = \Omega^2 r^3/G$$

Stellar Sizes

Stellar radii can be measured using eclipsing binary stars





orbital speed of the stars+relative separations => stellar radii

Scaling Relations

The equations of stellar structure and observational properties show that the luminosity and radius of a star are related to the mass of the star

$L \propto M^{\alpha}$; typically α=3-4.3

$R \propto M^{\beta}$; typically β~1

These relations will change as stars age

For the Sun: L=4e33 ergs/s, R=6.96E10 cm, M=2e33 gm

Energy Generation: Contraction

Kelvin-Helmhotz contraction: as a self-gravitating body contracts, it heats up and emits radiation

Virial Theorem: total energy (Thermal Energy + Gravitational Energy) of a collection of matter bound together by gravity is 1/2 the gravitational potential energy

Etot= TE+GE $$TE = -\frac{GM^2}{2r} = \frac{3}{2}NkT$$ for an ideal gas

$$\Delta T(r_1 \rightarrow r_2) = \frac{GM^2}{3nkT}\frac{1}{r_1 - r_2}$$ $r_2 < r_1$, ΔT increases

not hydrostatically stable, but important for contraction phases of stars and Jupiters

Nuclear Energy Generation

Stars are long-lived: age of earth a few billion years, so Sun must have existed for at least that long

FW Aston (1920): mass of He < mass of 4 H

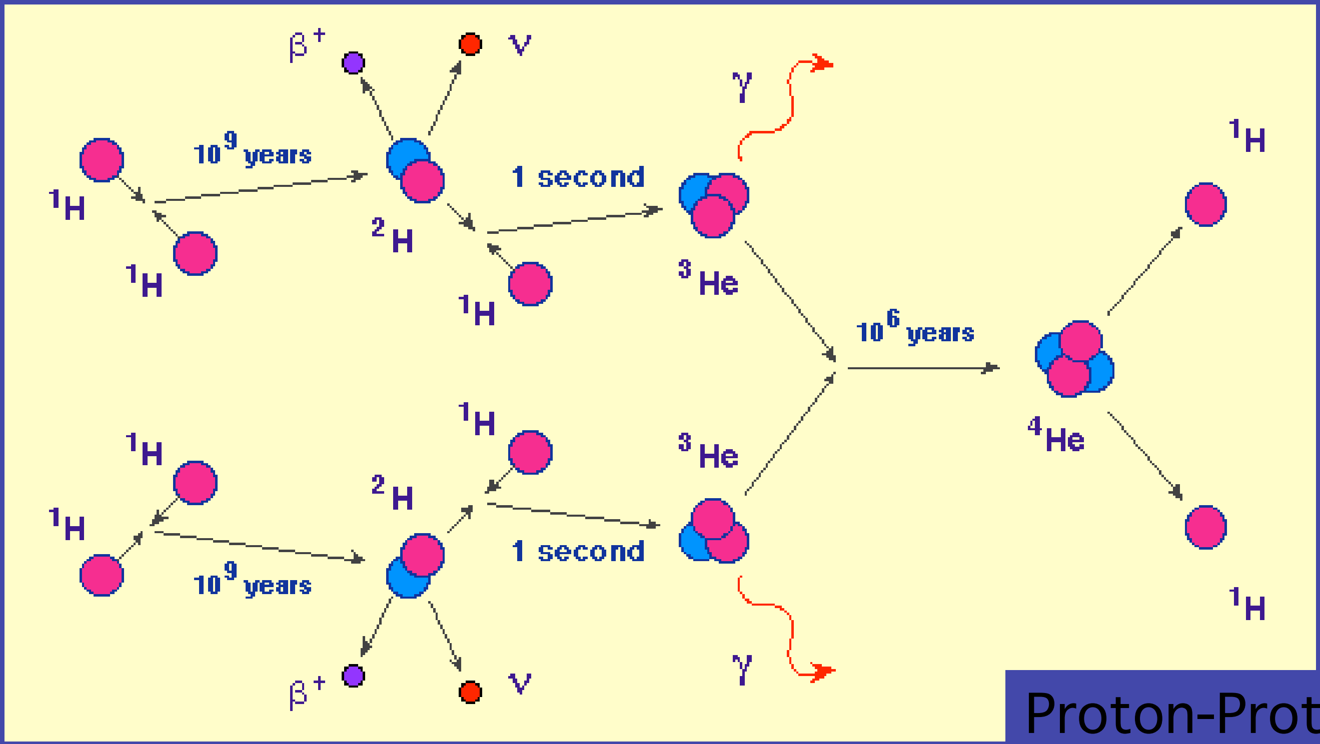
Eddington (1920): perhaps conversion of H to He in sun?

Means of stellar energy generation (in solar-type stars) solved in 1938 by Hans Bethe. Bethe showed that fusion of H in stellar core can provide enough energy to match observed luminosities

Requires high temperatures and densities to overcome the Coulomb barrier

$$\text{mass}(4p) - \text{mass}(\text{He}) = 0.03 m_p;$$

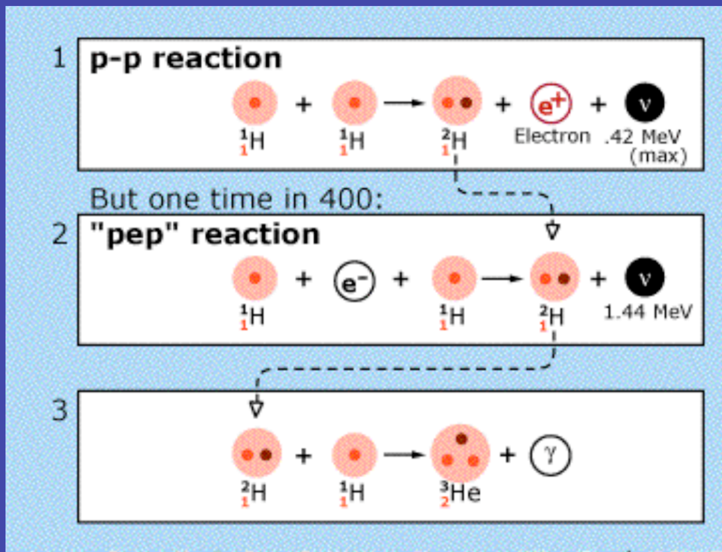
Reaction Times & Rates: PP chain

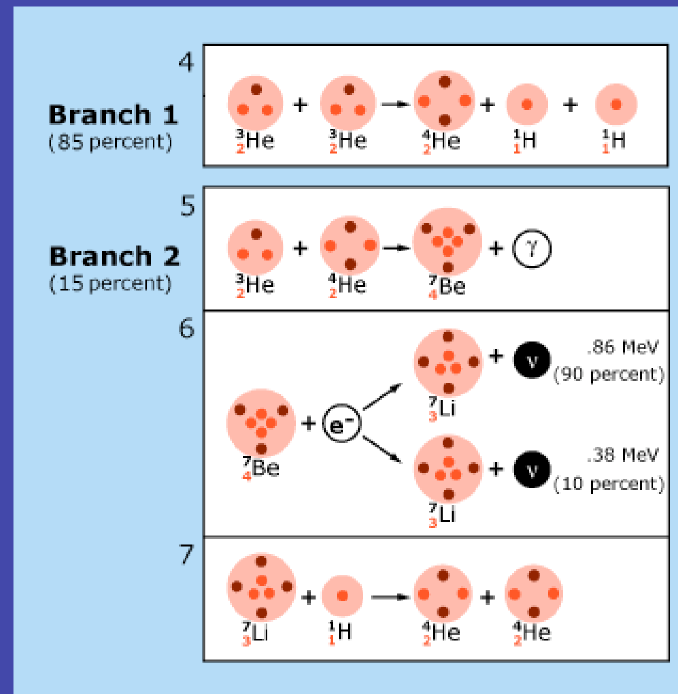


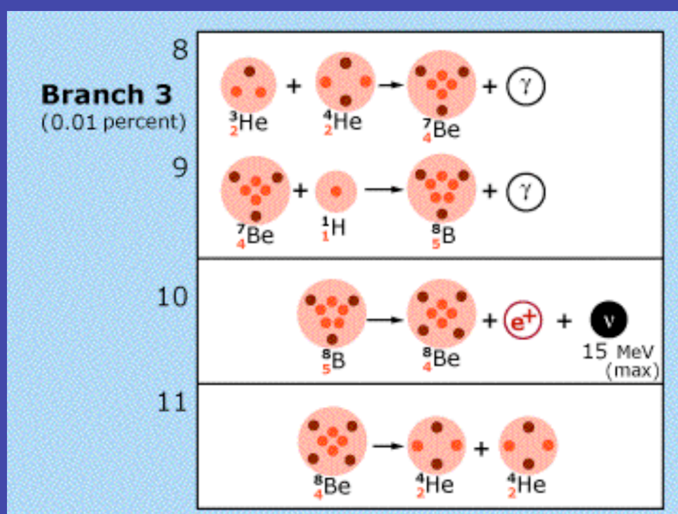
Proton-Proton (PP) chain

$$\varepsilon_{pp} = 2.5 \times 10^6 \rho X^2 \left(\frac{10^6}{T}\right)^{\frac{2}{3}} \exp\left(-33.8\left(\frac{10^6}{T}\right)^{\frac{1}{3}}\right)$$ ergs s^{-1} gm^{-1}

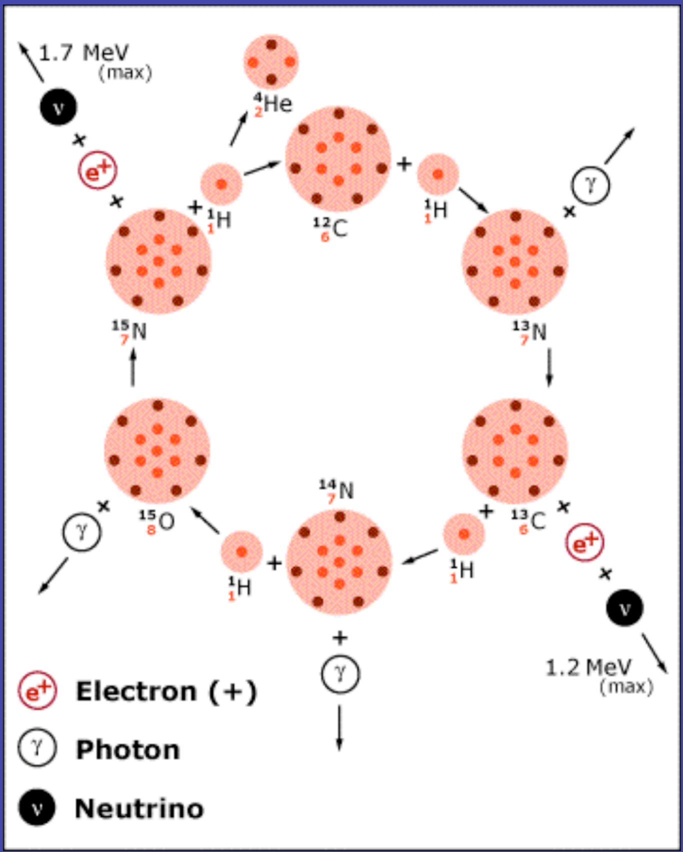
Alternate Paths







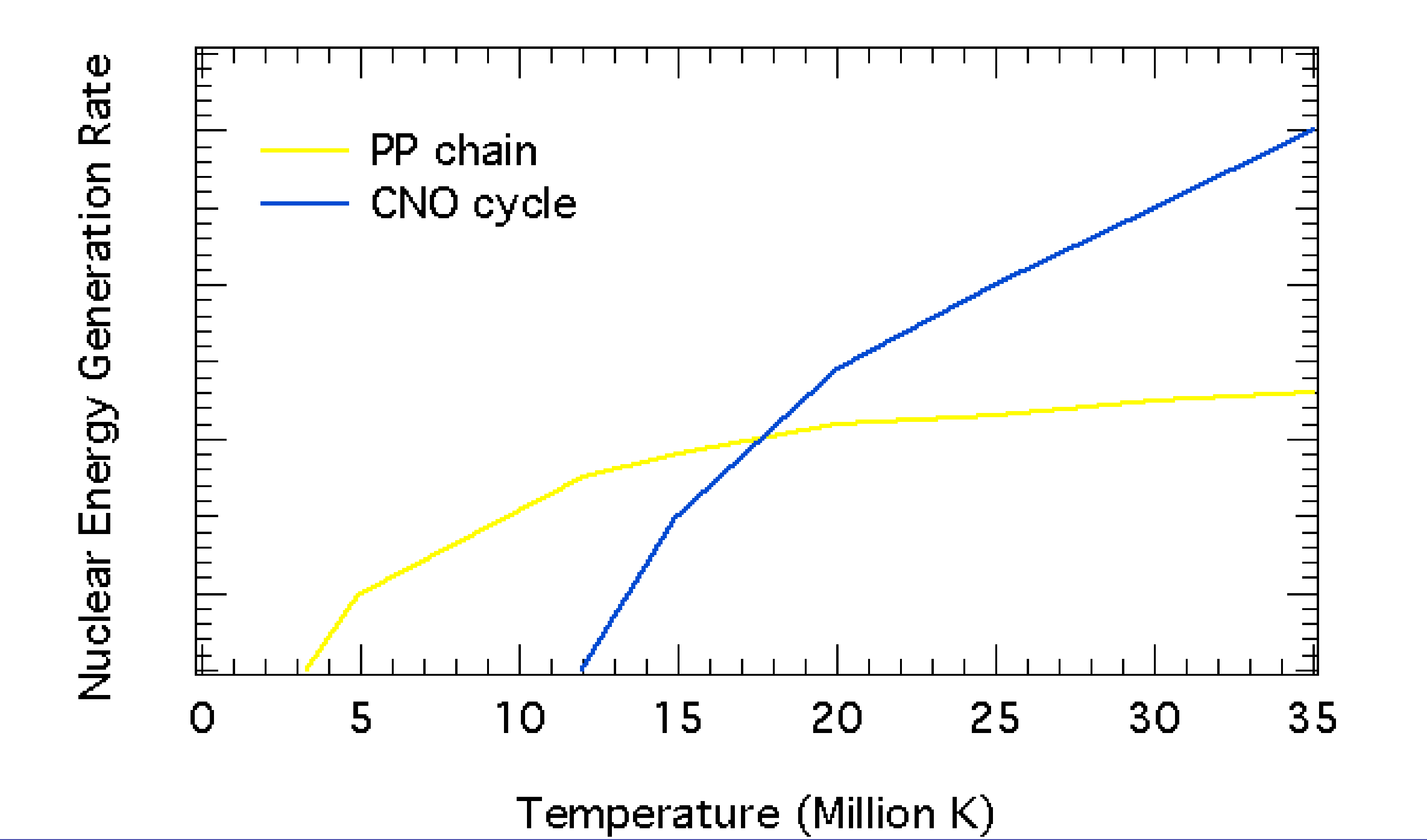
Other Alternatives: CNO cycle



Stars which contain carbon, nitrogen & oxygen can convert 4p to He via a nuclear reaction in which CNO acts as a catalyst

$$\varepsilon_{cno} = 9.5 \times 10^{28} \rho X X_{cn} \left(\frac{10^6}{T}\right)^{\frac{2}{3}} \exp\left(-152.3\left(\frac{10^6}{T}\right)^{\frac{1}{3}}\right)$$ ergs s^{-1} gm^{-1}

Comparison: PP vs. CNO



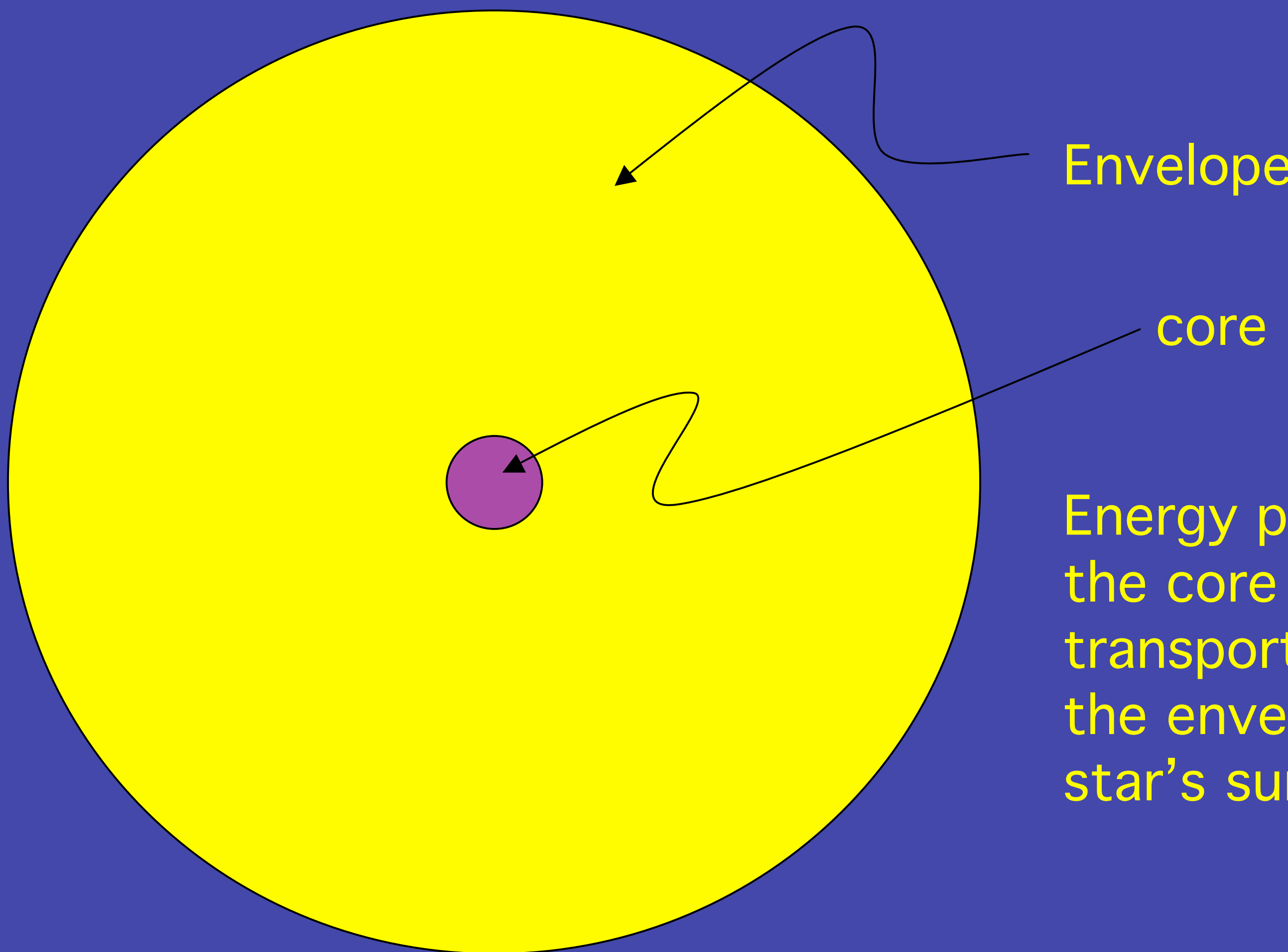
PP chain dominates at low temperatures; CNO cycle dominates at high temperatures

Stable Equilibrium

Because the energy production rates depend sensitively on temperature

- compressing star produces more energy in the core since as volume drops, pressure and temperature increase (assuming ideal gas laws apply): star will try to expand
- if the star expands, core temperature drops: less energy produced, star will shrink.
- as long as the H lasts, star can maintain hydrostatic equilibrium
- By Virial theorem, stellar temperature related to stellar mass, so more massive stars have higher core temperatures, and will generate energy via CNO cycle (which produces more energy at higher T’s)

Stellar Interiors

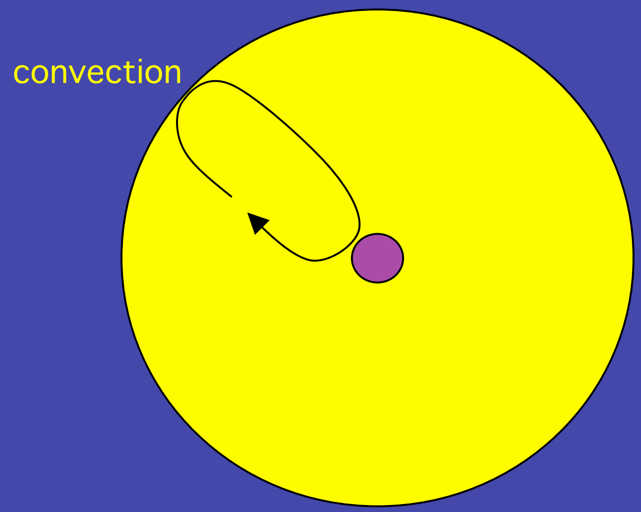


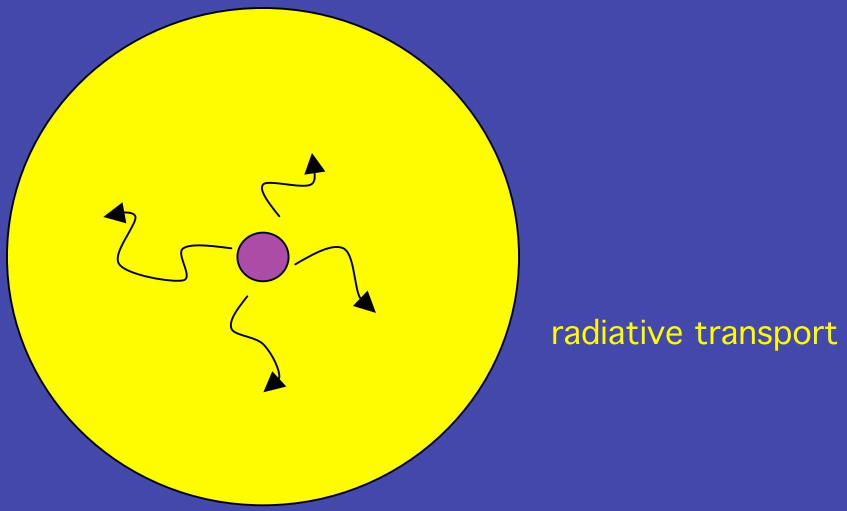
Energy produced in the core needs to be transported through the envelope to the star's surface

Energy Transport

Energy from the core gets to the surface via one of two ways:

- bulk mixing of hot and cold plasma (hot gas rises through cold gas)
- via photons





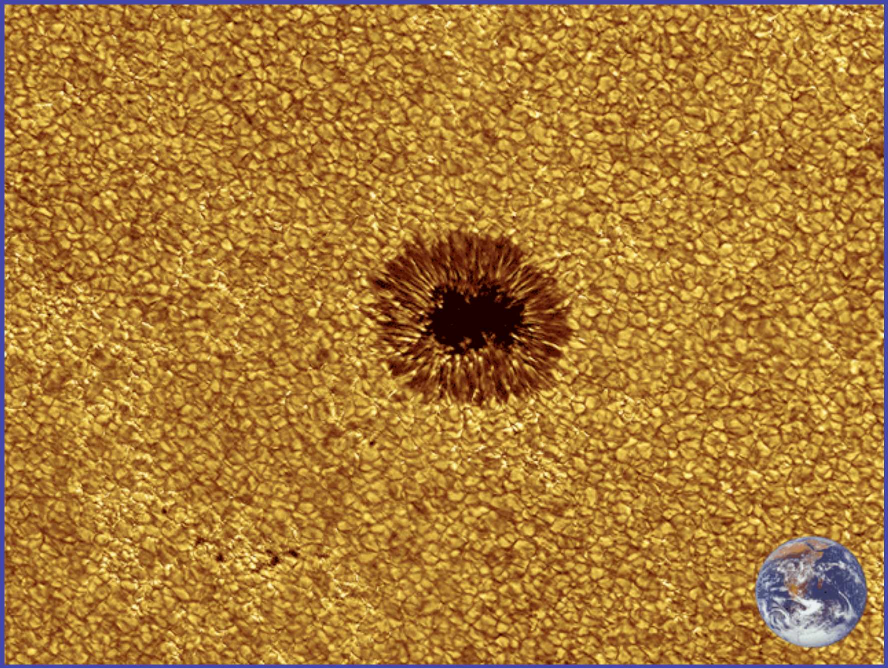
Interior Differences

Thermal gradient in the interior determines if the plasma is stable against convection

Lower-mass stars: have radiative cores and convective envelopes

Higher-mass stars: have convective cores and radiative envelopes

Stellar Atmosphere



Dutch Open Telescope, Sterrekundig Instituut Utrecht

This sequence shows emission from the sun ranging from the photosphere to a few thousand kilometers above the photosphere, around a sunspot.

Atmospheric Layers

The photosphere is the lowest layer of the stellar atmosphere; it is where all the radiation from the star emerges from the interior. Temperatures typically 2000-30,000 K

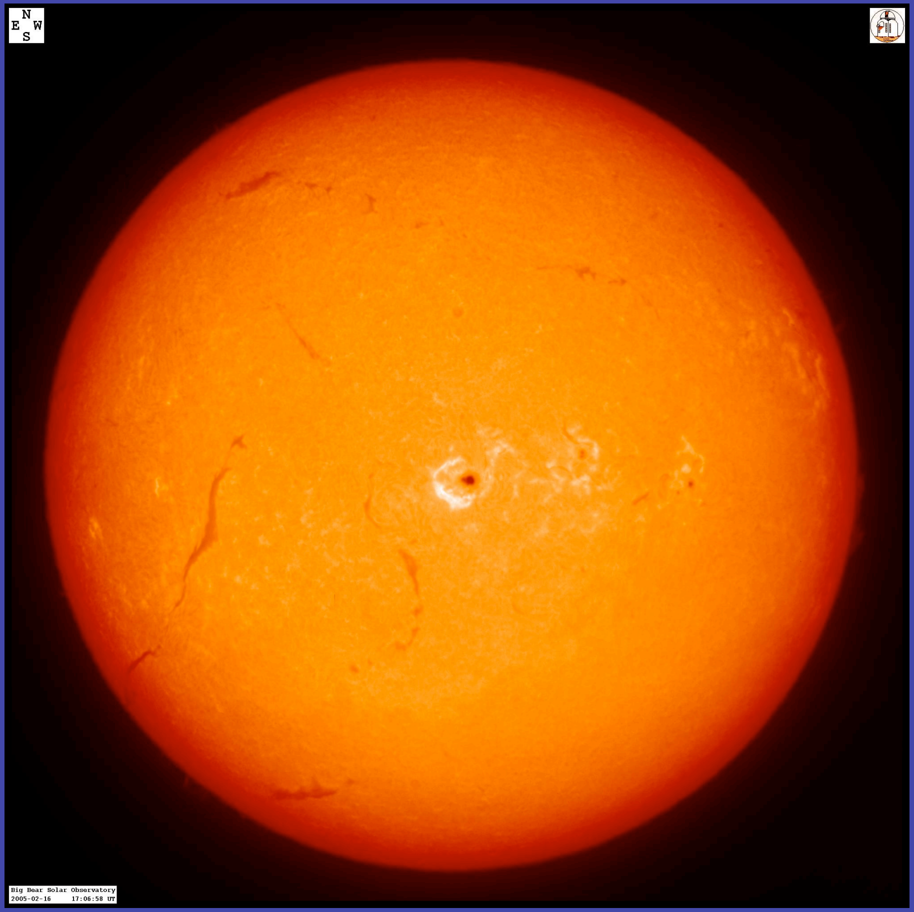
In low mass stars:

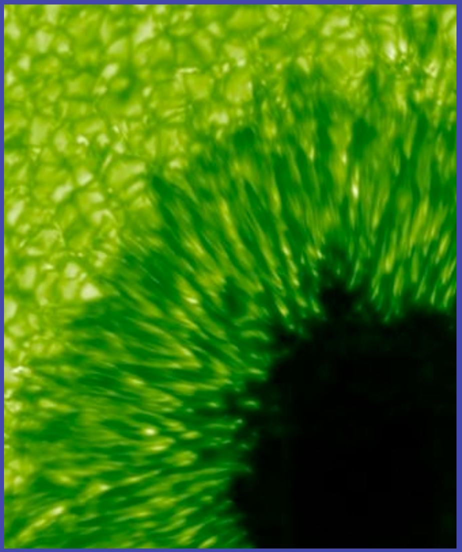
> Just above the photosphere is the chromosphere. In the sun the chromosphere is 2000-3000 km thick. Temperatures typically a factor of 5 or so higher than the photosphere
>
> Beyond the chromosphere is the corona, a low-density region of very hot (T~2 million K) gas extending out a stellar radius or so.

In high mass stars (M>10 Msun):

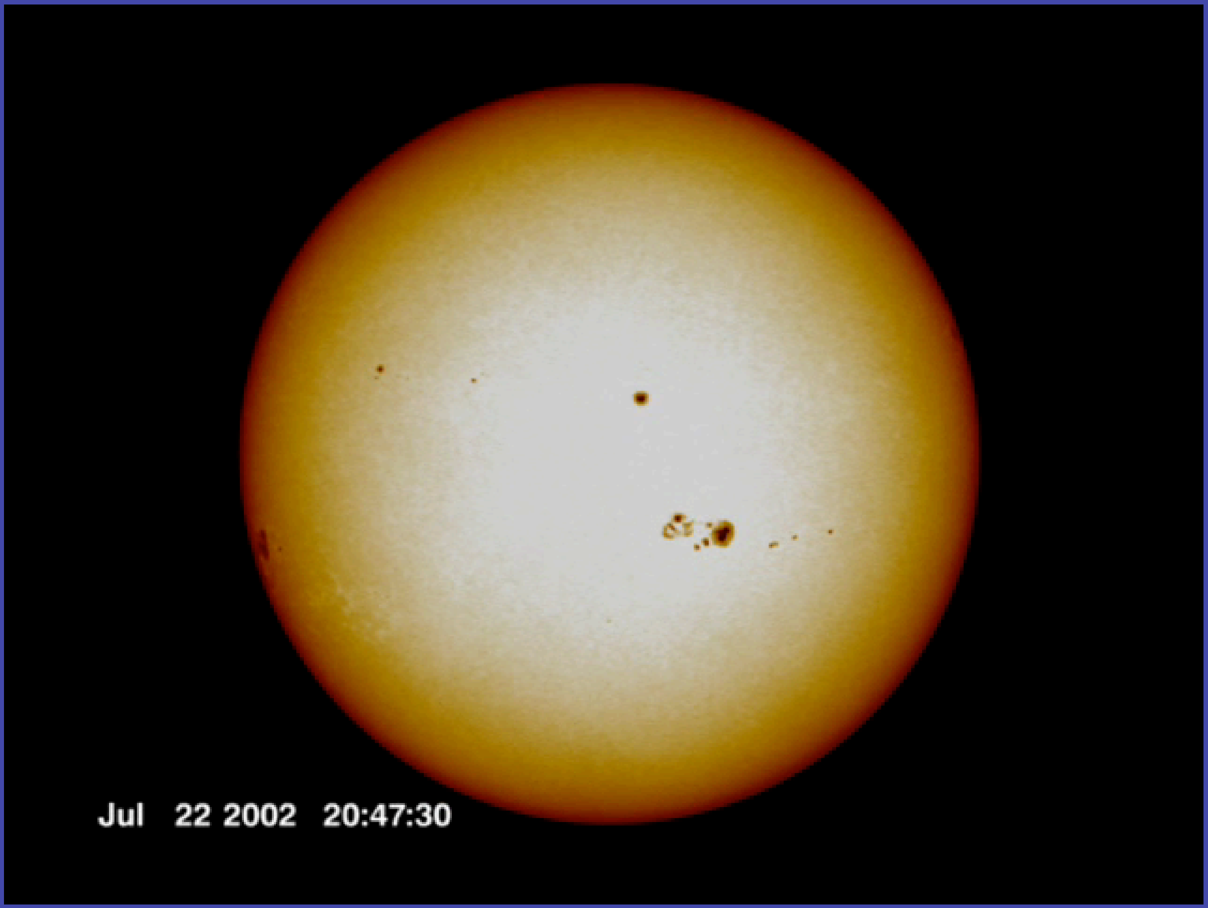
> Beyond the photosphere is the stellar wind

The Sun: A Typical Low Mass Star





High Energy Processes



Red: X-rays

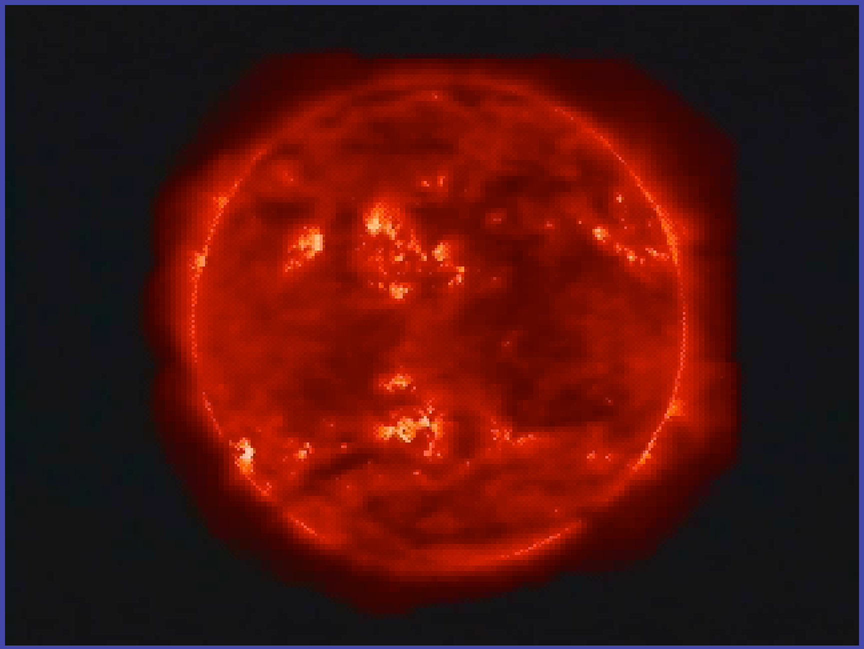
Violet: 2.2MeV emission from neutron capture

Blue: matter-antimatter annihilation

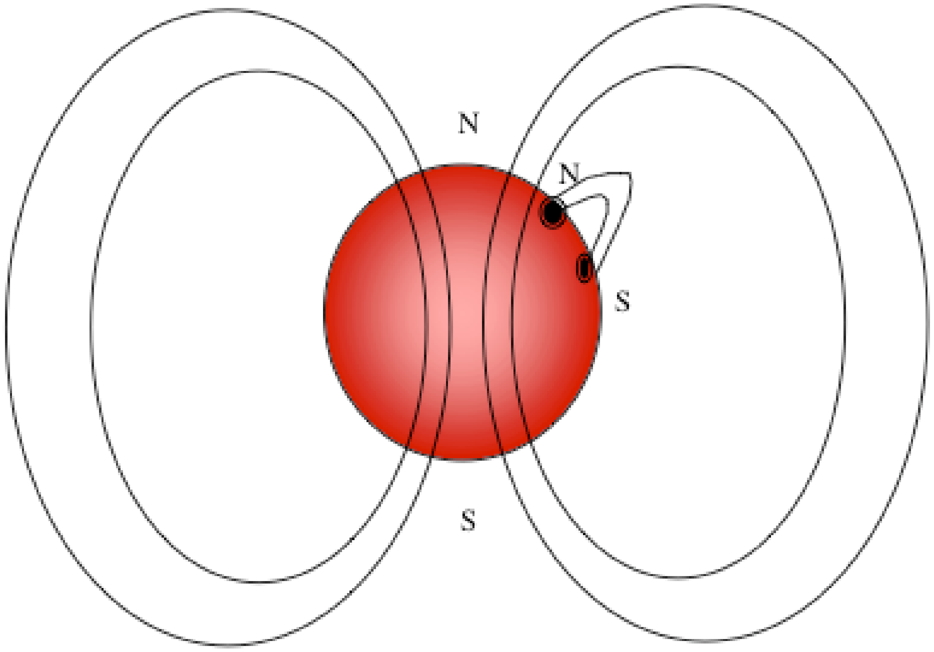
Types of Activity

Stellar atmospheric activity produces

- sunspots
- coronal loops & prominences
- stellar flares



Dynamo Effect



$T = P/nk$

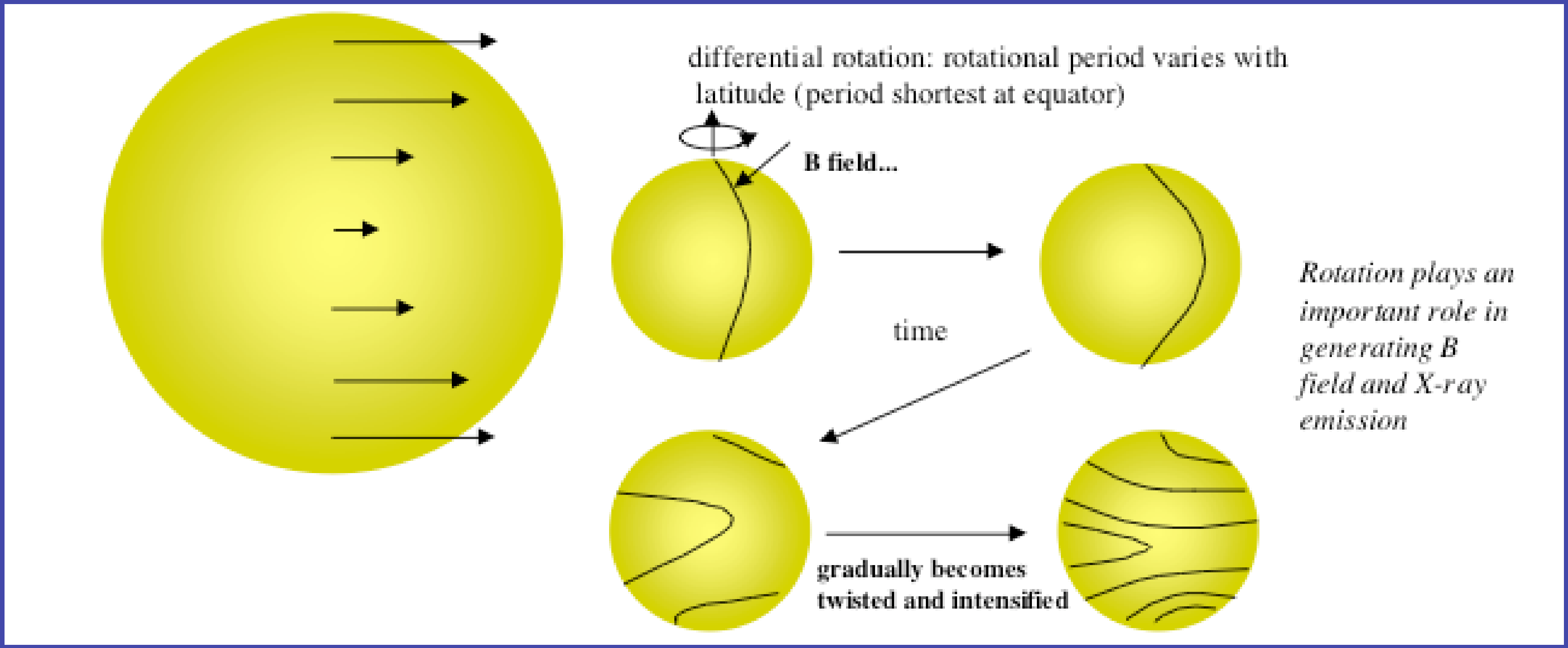
$P = P_g + P_B$

$P_B = B^2/8\pi$

Magnetic heating thought to be the dominant heating mechanism in the corona (as the B field varies, the size and temperature of the corona varies too).

Rotating stars with convective interiors generate magnetic field via the “dynamo effect” similar to the earth’s magnetic field

Differential Rotation

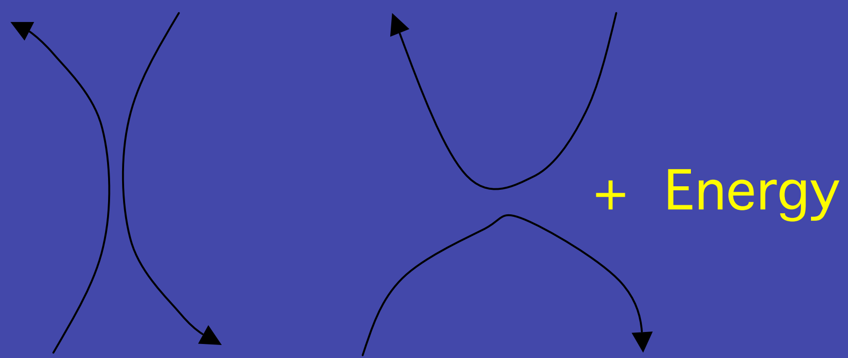


Magnetic Effects

Changing local magnetic field strength produces a number of observable effects:

- intense magnetic field suppresses convection to photosphere: sunspot. Usually occur in pairs as the footprint of a magnetic loop.

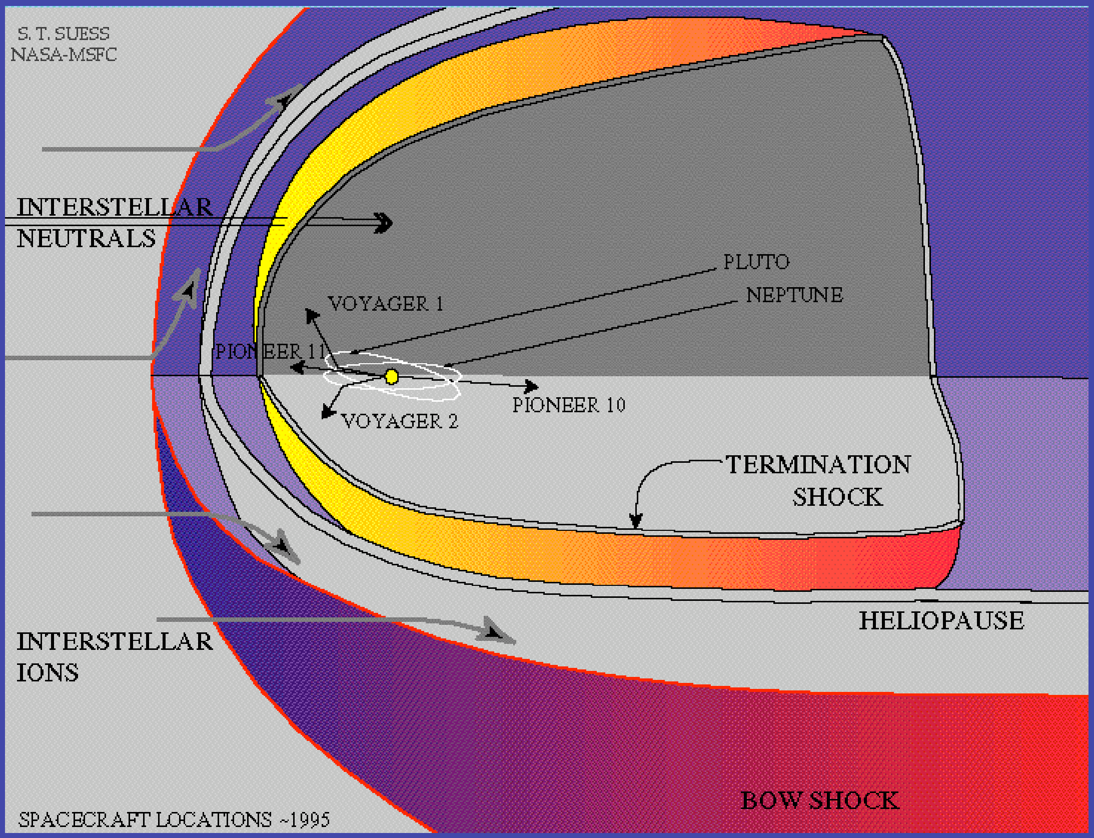
- magnetic field lines in the corona can get twisted, produce high magnetic density. Lines of opposite polarities can connect releasing large amount of energy to heat the corona to temperatures of millions of degrees



B field lines

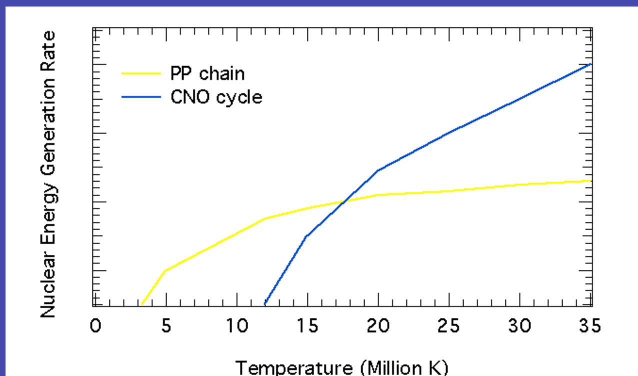
Effects on the ISM

The high temperatures of the corona provide enough energy to gradually drive matter away from the sun, especially where the magnetic fields are weak.



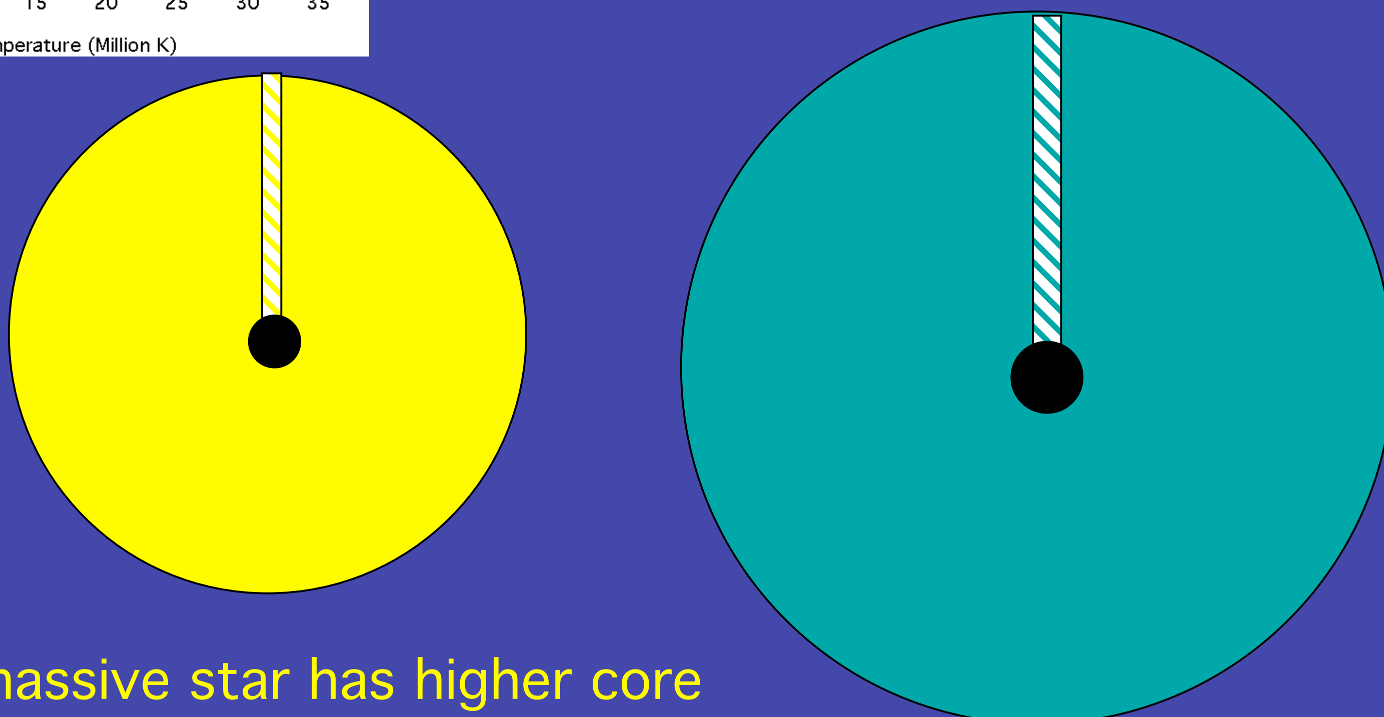
Interaction of the solar wind (and the sun's motion through the Galaxy) with the ISM forms the heliosphere.

Mass Differences



•In hydrostatic equilibrium, gravitational force inward = pressure force outward

•core pressure (hence temperature) set by weight of material above the core



more massive star has higher core temperature

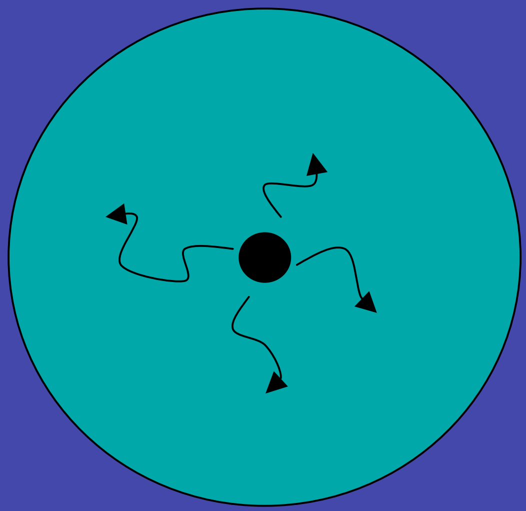
Low vs. High Mass

As you add mass to a star* the following happens:

- more energy is generated in the core: more energy must be lost from the photosphere
- more energy is deposited into interior, increasing internal pressure and temperature
- More mass = higher surface temperatures and larger radii

*non-degenerate

Interiors of Massive Stars



Massive stars have radiative envelopes:

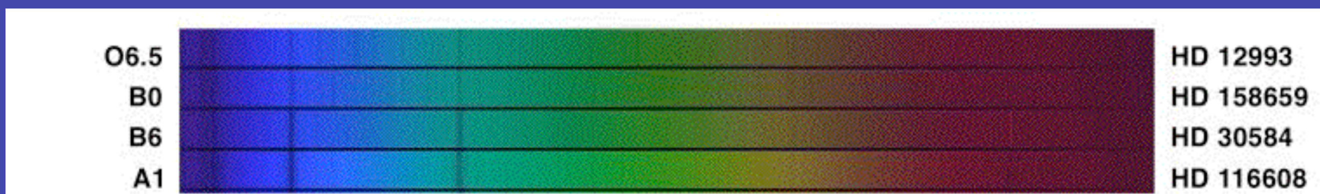
- no convection to surface
- no dynamo
- no magnetic activity?

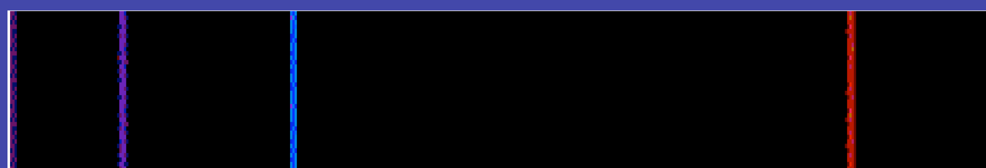
Massive stars should not have magnetically-driven activity cycles via the dynamo effect

(but perhaps magnetism produced by the accretion of the IS field?)

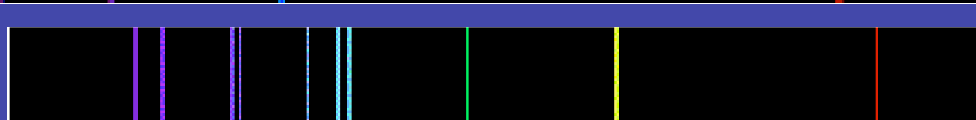
Photospheres

H lines weaken (because H is ionized by the large stellar flux





Balmer lines of H (N-2 transition)



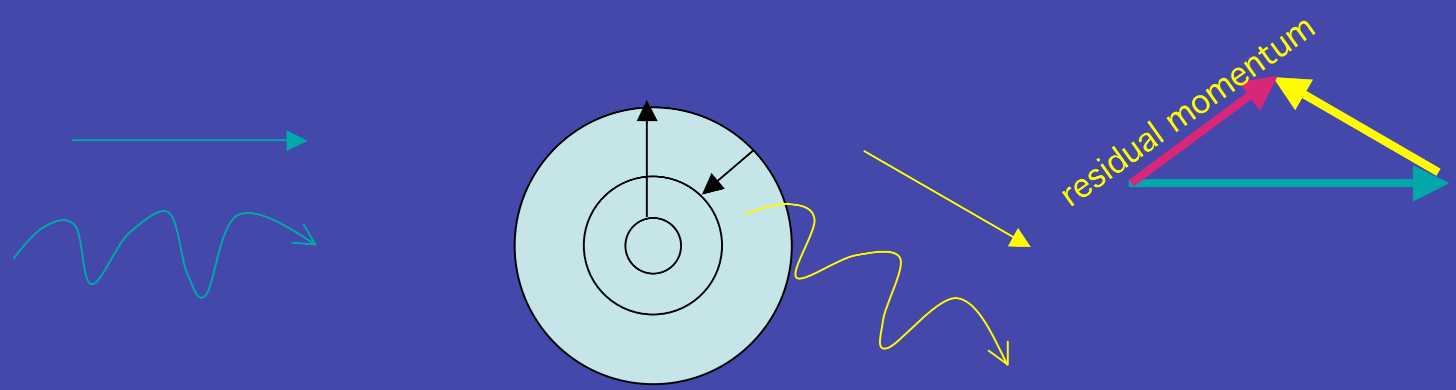
He lines

Sp. Type	Temperature
O	> 30000K
B	12000-30000K
A	8000-12000K
F	6000-8000K
G	5000-6000K
K	4000-5000K
M	2000-4000

Winds

At the photospheric temperatures of O & B stars, spectrum will peak in the UV (Wien's law)

UV photons carry considerable momentum



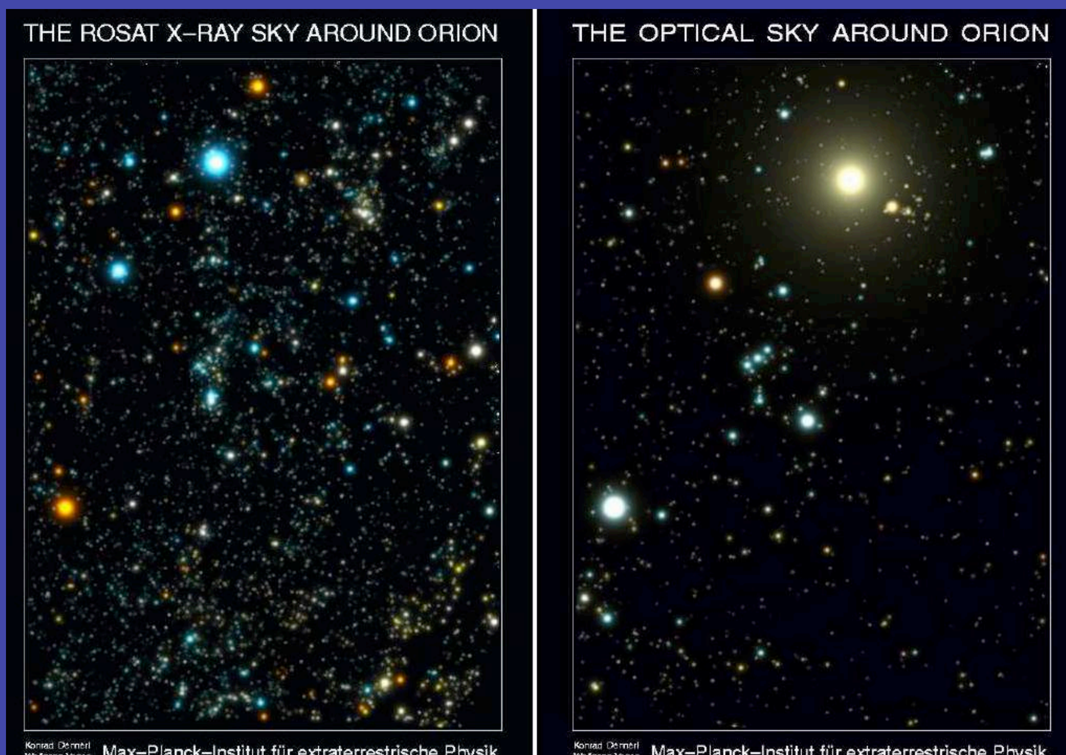
Absorption of UV photon momentum results in an outward motion of gas atoms away from the photosphere: A Stellar Wind

Characteristics of Winds

Parameter	Solar Type	OB type
mass loss rate	10^{-14} Msun/yr	> 10^{-6} Msun/yr
Speed	300-600 km/s	1000-3000 km/s
Kinetic Luminosity	$\sim 10^{26}$	$\sim 10^{35}$
Effect on Evolution	minimal	significant

High Energy Emission from Massive Stars

Lack of magnetic dynamo => lack of magnetic activity => little high energy emission?

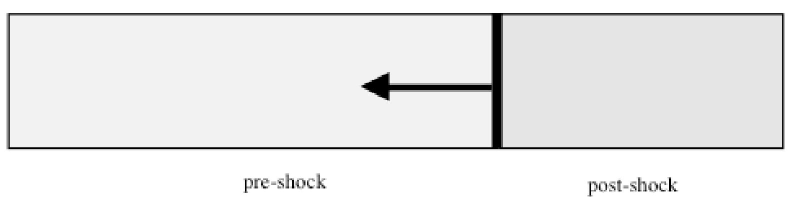


Actually massive stars are relatively bright X-ray sources (and perhaps gamma-ray sources, or sources of cosmic rays)

Emission produced by shocks created by the radiatively-driven wind

Radiative Instabilities and Shocks

Radiative driving is unstable: material farther from the photosphere will be shadowed by inner material and feel a lower driving force, eventually colliding with faster-moving inner material.
Collision of the outer and inner wind material will produce strong shocks in the wind



for an ideal gas and a strong shock(shock velocity >> sound speed c_s),

$$T_{post\text{-}shock} = 5/4\, M^2\, T_{pre\text{-}shock}$$

where M is the Mach Number $M = V_{shock}/c_s$

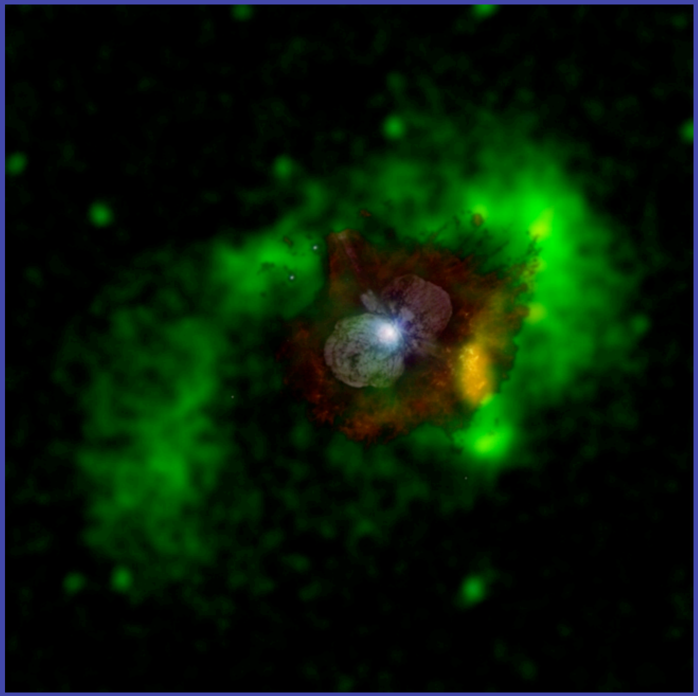
at velocities of winds, and speed of sound (~10 km/s) temperatures of millions of degrees can be produced.

Other Collisions

Winds can also collide with:

- nearby circumstellar clouds
- the wind from a nearby (companion?) star

Which can also produce X-ray emission

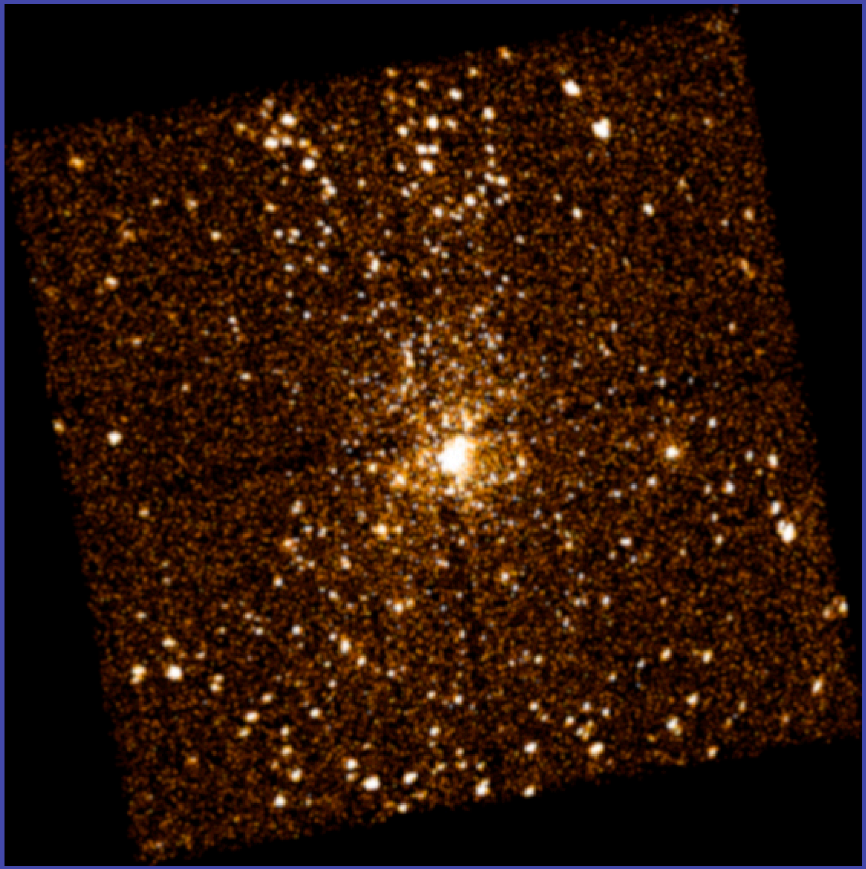


X-ray Image of Eta Carinae (green/white), compared to an HST optical image (red/blue). X-rays are produced by interaction of ejecta with surroundings, by wind colliding with the wind from another star, and probably from the unstable winds themselves

Importance of High-Energy Observations

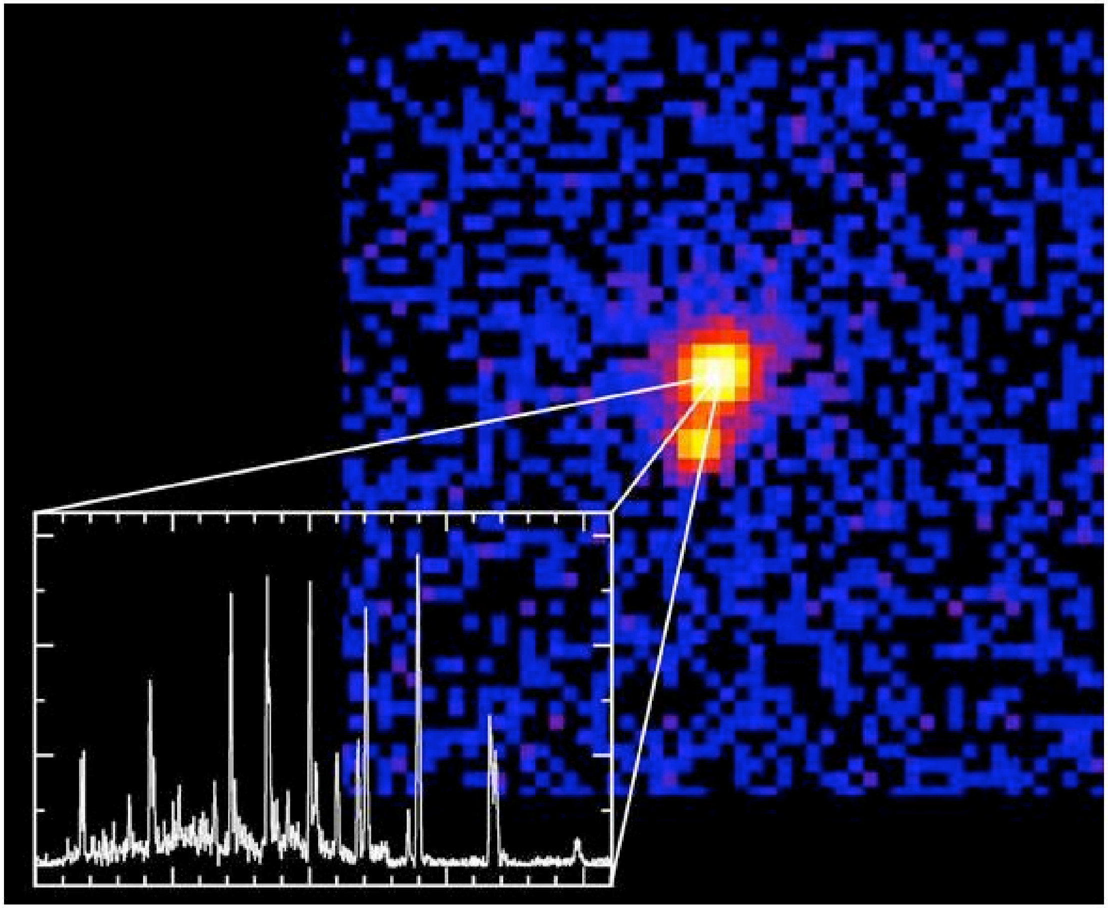
- X-rays can penetrate through large amounts of absorption
- X-ray emission can have a significant influence on the circumstellar environment of young stars through photoionization
- Stellar activity in low-mass stars gives a better idea of coronal activity
- X-rays from high mass stars give an understanding of the structure of the wind, and the wind dynamics
- Finding hidden binaries via wind-wind collisions
- Particle acceleration at shock fronts can produce cosmic rays

Probing Star Formation



X-ray image of Orion Nebula cluster reveals active dynamos in young stars

Dynamos in Massive Stars?

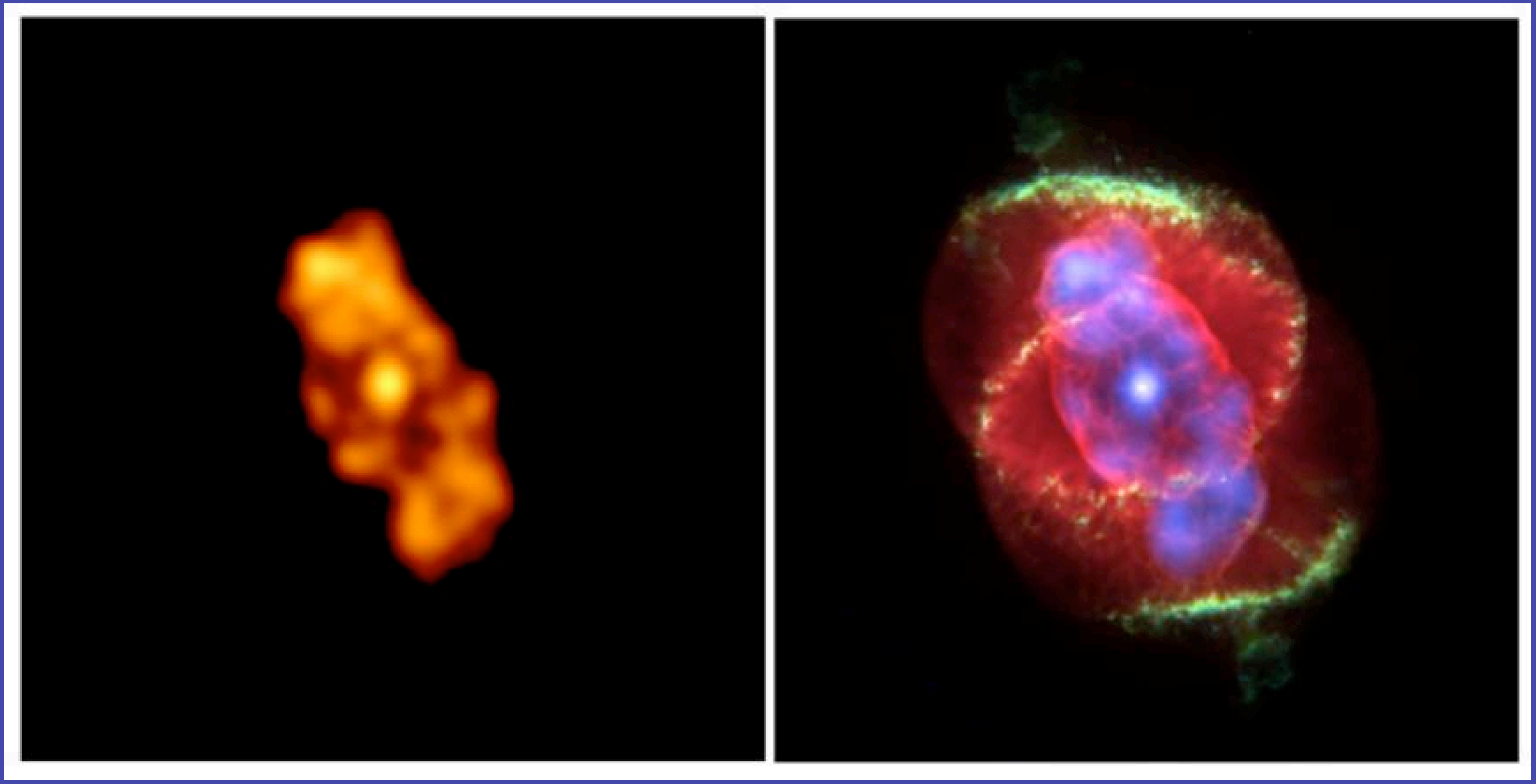


HETG emission line spectrum of the massive star Zeta Ori

Solar Coronal Loops

Lines form at unexpectedly high densities

The Cat's Eye



OY Car eclipse